SOFIA Upper Deck Research Facility: A unique atmospheric observation platform for the next 20 years

A mission concept in response to the NRC decadal survey RFI

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Abstract: SOFIA is the NASA/DLR "Stratospheric Observatory for Infrared and Sub-millimeter Astronomy" – a world-class astronomical observatory with a projected 960 flight hours/year for 20 years. It will operate out of NASA Ames Research Center, and also be deployed to locations worldwide, including the Southern hemisphere. New interdisciplinary scientific investigations in Earth Sciences and astronomy are feasible if a research facility can be established on the currently almost empty Upper Deck and cargo bay of the SOFIA B-747 aircraft for measurements during nominal operations.

In order to investigate the science questions that can be addressed uniquely from a SOFIA Upper Deck Research Facility (SURF), NASA's Space Science APRA program and NASA's Earth Science Enterprise co-sponsored the "SOFIA Upper Deck Science Opportunities Workshop" at NASA Ames Research Center on June 22 - 23, 2004. Fifty participants from five countries put forward suggested science studies that take advantage of flying on an operational aircraft for: a) long term (20 years) and b) many flight hours/year (960 hours). Extended abstracts are posted at: http://surf.arc.nasa.gov. The following mission concept summarizes and updates only the relevant Earth Science results from the workshop.

Observations from SOFIA complement satellite observations and focused missions involving research aircraft. Standard payloads would include observations similar to the European MOZAIC program and a suite of instruments that would be rotated in and out based on an observation plan. With its 20 year expected lifetime, SURF will provide validation opportunities for several generations of satellites and long term monitoring of climate change in the crucial tropopause region. Regular SURF atmospheric trace gas profile measurements during ascent and descent will provide valuable input to agencies like NOAA, EPA, and the California Air Resources Board that study long range transport of pollution entering the US and its health impacts. Operating out of NASA Ames, SURF will provide new data over the undersampled Pacific, complementing the MOZAIC program, which covers the US East Coast.

In contrast to other research aircraft like the NASA ER-2 and NSF HIAPER, there is ample space for scientists on board. Thus, SURF could have an important role in providing the atmospheric science community with a unique test bed for instrument development and low cost access to flight, since no mission will have to be scheduled and flight cost are covered by the astronomical observations. The technical challenges of integrating scientific instrumentation onto an operational FAA certified aircraft can be addressed by including knowledge gained from the European MOZAIC and CARIBIC program and the NSF HIAPER aircraft.

Our mission proposal addresses the following themes: 1) Earth Science Applications and Societal Needs, 3) Weather (including chemical weather and space weather) 4) Climate Variability and Change 5) Water Resources and the Global Hydrologic Cycle and 6) Human Health and Security. Capabilities as presented here are also called for in the 10-year implementation plan of the Global Earth Observation System of Systems (GEOSS)

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Introduction

NASA and the German Aerospace Center DLR are working together to create the Stratospheric Observatory for Infrared Astronomy (SOFIA) — a Boeing 747SP aircraft modified by L-3 Communications Integrated Systems to accommodate a 2.5 meter reflecting telescope developed in Germany (e.g., http://sofia.arc.nasa.gov/). Universities Space Research Association (USRA), an association of 80 Universities, is the prime contractor for SOFIA. USRA and its subcontractors will operate SOFIA for NASA and DLR. The instruments for the observatory are being designed and constructed at universities and NASA centers across the nation as well as in Germany. The SETI Institute is partner with the Astronomical Society of the Pacific in conducting the Education and Public Outreach Program for SOFIA. SOFIA will be operated out of NASA Ames Research Center. Science and final engineering flights are scheduled to start at a low rate in late 2006. It might take another two years before science flights will commence at a rate of up to four 8-hour flights every week for a total of 960 hours/yr.

Figure 1. Sofia Upper Deck layout with location of water vapor monitor and pumps (Image: DLR). There are 10 windows at each side of the cabin.

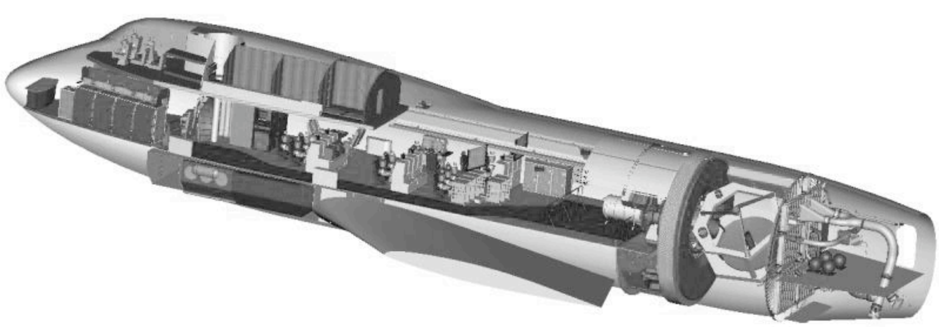

Figure 2. Location and some details of upper deck inside SOFIA. The final configuration details of this unused area are not settled and may be modified (Image: DLR).

The main instrument of this airborne observatory is a 2.5 m mid-IR and sub millimeter telescope, but there is a huge potential for Earth Science research from instruments in an otherwise nearly empty upper deck cabin and cargo bay (Figure 1). The upper deck is the most stable platform for instruments and is located before and above the engines and wings for optimum air and dust sampling (Figure 2). Any weight introduced on the upper deck will help balance the telescope assembly in the tail. Hence, choosing to have an Upper Deck Research Facility is choosing to replace ballast with scientific instruments. Currently, only a Water Vapor Monitor will be stationed there, in the second window from the back of a row of 10 such windows, in addition to vacuum pumps that will pump on science instrument cryostat vacuum enclosures. The windows are tilted at 27.8 degrees upward and permit viewing ±40 degrees in azimuth and between 0 - 68 degrees in elevation, if equipped with the right window materials. The experiments would need to be uniquely suited for (semi-) autonomous operation for long times, with known flight paths pre-determined by the needs of the main observatory. Each such research opportunity needs to be investigated for its requirements, cost, and impact on SOFIA operations, and carefully designed not to interfere with the main facility. Other potential equipment sites on SOFIA (e.g. cargo bay) require airframe modifications for windows or sampling probes.

SOFIA will fly out of NASA/Ames at night for most of its life, sampling air masses between 25 and 55 degrees of latitude (with a similar range in longitude). In order to minimize interference from water vapor, the level flight legs will be (as much as possible) confined to the stratosphere. Even with these constraints, SOFIA will still sample a broad range of air masses because of the large fluctuations in atmospheric winds. Figure 3 shows the sampling of air masses as defined by potential temperature (theta) and potential vorticity (PV). These represent two quasi-conserved quantities along air mass trajectories and are reasonable first-order representations of the character of an air mass in the lower stratosphere.

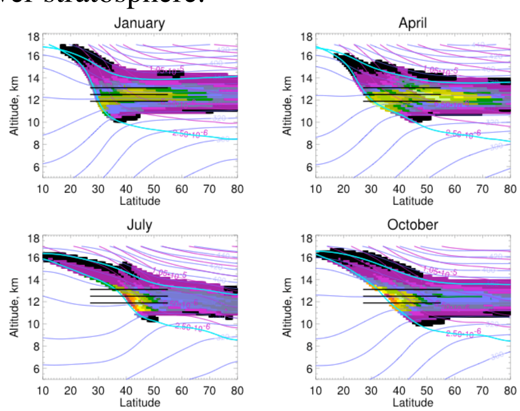

Figure 3: Sampling of air masses by SOFIA as defined by potential temperature (theta) and potential vorticity (PV). The colors show relative frequency of observation of particular theta-PV combinations, with the colors plotted at the mean latitude-height position of each theta-PV combination. Warm colors are high frequency, with magenta and black representing the lowest frequency. The lowest cyan line represents the tropopause (all level flights are assumed to be in the stratosphere), and the three horizontal black lines represent the operational range and altitudes of SOFIA.

The basic conclusion is that, in all seasons, air masses whose mean positions range from 10 to 80 N latitude, and 10 to 16 km altitude are sampled by SOFIA, with the broadest ranges occurring during winter and spring. Though sampling is concentrated near the subtropical jet in summer and fall, there is still significant sampling of air from higher latitudes. Notably, nearly the entire lowermost stratosphere (stratosphere below 380K of potential temperature, the upper cyan line) is sampled. This region mixes actively with the troposphere in an as yet poorly characterized way, contains a significant portion of the ozone layer, and also is a region of significant (and poorly understood) ozone loss.

In addition to the sampling described in Figure 3, the aircraft will do two profiles per flight (about 6 profiles per week) into Ames. Again, because of the fluctuations in winds, a substantial part of the troposphere will be sampled, as shown by the broad range of back trajectories in Figure 4. With the planned global deployments in the future, the observations will become truly global as well.

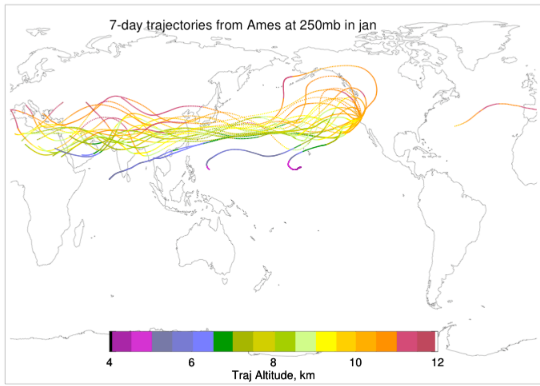

Figure 4: 7 day back trajectories from NASA Ames starting at 250 mbar.

The SURF observations offer to fill a gap between satellite instruments and the traditional atmospheric research aircraft by providing similar spatial resolution as the research aircraft, but at frequencies and over periods more similar to the satellite observations.

SOFIA will carry teachers and students along for astronomical observations. Therefore, our proposed program can tap directly into this education and outreach effort and broaden the experience of flying on SOFIA.

Mission concept, observational variables

NASA's Space Science APRA program and NASA's Earth Science Enterprise co-sponsored the "SOFIA Upper Deck Science Opportunities Workshop" at NASA Ames Research Center on June 22 - 23, 2004 to investigate the science questions that can be addressed uniquely from a SURF (http://surf.arc.nasa.gov). Fifty participants from five countries (see Appendix for complete list) presented their science studies that take advantage of flying on an operational aircraft. These experiments would be prohibitively expensive using traditional missions with research aircraft. We compiled a basic set of experiments that would benefit from the high altitude (39,000-41,000 ft) flight level night-time flights. These examples illustrate various aspects of 1) what research activities may be undertaken and the expected products, 2) what range of community facilities would be needed, and 3) what may be done at the level of funding proposed here. From these and other experiments a program should be developed and implemented at the earliest possible time when SOFIA is fully operational. By accommodating several instruments in the upper deck, we can guarantee a continuous stream of interesting data and periodic highlights.

The experiments address various aspects of weather (including chemical weather and space weather), climate variability and change, water resources and the global hydrological cycle, and human health and security.

Air pollution

From SURF a wide range of trace gas components including hydrocarbons, halocarbons, sulfur compounds, and organic nitrates can be measured. These compounds play key roles in the chemistry and physics of the atmosphere, including stratospheric ozone (O3) depletion, tropospheric O3 formation, radiative forcing, and the oxidative capacity of the atmosphere. In addition, trace gas measurements from whole air samples provide detailed information on air mass sources, transport, and photochemical processing that is useful to atmospheric chemistry and dynamics investigations. Long term measurements of mercury aboard SOFIA could provide important clues about transport pathways of this poorly understood toxic pollutant, in particular with a source in Asia.

A current focus of research concerning tropospheric composition and air quality is the amount of ozone produced within the United States and advected to downwind locations such as Europe. Insight into these issues requires trace gas profiles from key locations within the United States at a spatial and temporal frequency adequate for computing the daily ozone gradient across the country. Current ozonesonde profiles are measured once per week at four eastern and central USA sites. The only site on the west coast of the USA that can assess the background ozone entering the USA at weekly intervals is the coastal site of Trinidad Head (41 N). In addition, the European funded MOZAIC program measures ozone, water vapor and CO at various airports across the USA but the frequency of the profiles is variable and the profiles only extend to 10 to 12 km. MOZAIC sampling on the east coast occurs year round but west coast sampling is intermittent. At present the availability of in situ vertical trace gas measurements throughout the tropospheric column is not adequate for determining day to day, or even week to week fluctuations of ozone across the entire USA. The current sampling rate of once per week at the ozone sonde sites is only adequate for assessing intraseasonal variation. To determine the quantity of trace gases entering the USA west coast, additional profiling is essential at greater temporal and spatial scales than currently available. Trace gas measurements beyond water vapor and ozone from the NASA 747 would help fill the large gap in west coast trace gas profiling. While Trinidad Head is just a few hundred kilometers to the north, even an increase in ozonesonde launch frequency to once per day would not be as beneficial as measurements from the NASA 747 because the limitations of just ozone and water vapor means polluted air masses cannot always be distinguished from air masses of stratospheric origin. In contrast, air masses sampled by the NASA 747 could be clearly identified as having a major anthropogenic or stratospheric component. While ozone profiles at other sites across the country are unlikely to achieve consistent daily frequency in the near future, these sites are occasionally augmented to have daily launches during regional air pollution studies as occurred during the recent ICARTT experiment in the northeastern USA and Canada. During these experiments the combination of the NASA 747 profiles and the ozonesonde profiles will have great value for establishing the longitudinal ozone gradient across the USA.

NOAA and the California Air Resources Board have expressed interest in increased sampling to study air pollution and likely EPA would participate in these efforts too.

Far infrared to study climate change

The far infrared (far-IR, 15-100 μm) remains essentially unobserved directly despite containing up to 50% of the planet's outgoing longwave radiation and being a major factor in the planet's greenhouse effect. Far infrared measurements by instruments such as Far-Infrared Spectroscopy of the Troposphere (FIRST) (funded by the Instrument Incubator Program (IIP) of the NASA Earth Science Technology Office (ESTO)) on SOFIA offers unique opportunities to investigate water vapor spectroscopy, cirrus radiative properties, the Earth's greenhouse effect, and water vapor feedback.

Flying FIRST on SOFIA offers a unique potential for scientific discovery by providing unprecedented endoatmospheric views of the far-IR spectrum of the Earth's atmosphere. In the figures below, we show examples of FIRST spectra as could be obtained from SOFIA in an uplooking mode from various flight altitudes. These simulations show both the computed spectra and the noise level for a noise equivalent temperature of 0.5 Kelvin, the FIRST design requirement, in the red line. Also shown in each figure is the expected noise level for the average of 100 spectra (pink line). As is evident, the FIRST on SOFIA offers the opportunity to measure the downwelling far-IR spectrum throughout the middle and upper troposphere, into the vicinity of or above the tropopause, depending on latitude. These data would serve as fundamental validation spectra for models of water vapor, the natural greenhouse effect, cirrus radiative forcing, and temperature-water vapor feedbacks. SOFIA provides an excellent opportunity for regular, long-term (20-year) airborne monitoring of important trace gases that impact global change, in particular chlorofluorocarbons (CFCs) and their replacements, halons (e.g. H-1211), hydrocarbons (e.g. ethane, propane, n-butane), dimethyl sulfide (DMS), and methyl bromide (CHBr) that would nicely complement the far infrared observations and contribute to our understanding of climate change. NOAA has expressed interest in these trace gas measurements.

Aerosol Observatory

A quasi-permanent Aerosol Observatory will be located in the upper deck of SOFIA to carry out routine measurements during normal periods, and to be available for measurements of stratospheric and/or upper tropospheric aerosols during special periods like the period following a volcanic eruption, a large forest fire or a disaster such as a nuclear accident.

Besides routine monitoring, the greatest value of the facility would be in cases when unexpected or unusual atmospheric perturbations take place. There have been several cases in the past twenty years when the scientific community lost opportunities to carry out valuable atmospheric observations due to the lack of an airborne aerosol observatory. In some other cases, the need to make the observations required a hasty and expensive aircraft campaign. We give three examples of situations in which the SOFIA SURF Aerosol Facility would be particularly valuable.

Volcanic Clouds

An example of a case in which the scientific community found itself unprepared was the eruption of Mt. Pinatubo in June 1991. A thick cloud of volcanic dust and gas quickly spread around the globe in a narrow band. This material then gradually spread towards the poles, enveloping the Earth. It is believed that during this time the nature of the cloud changed, starting out primarily as dust and then, due to the conversion of SO2 to sulfate and the nucleation of sulfuric acid particles, into a sulfate aerosol.
The Pinatubo volcanic cloud was so thick that SAGE II, the primary instrument for measuring the stratospheric aerosol, was not able to determine the extinction of the layer because the transmission was too low for the detector to measure. Unfortunately, the scientific community was not prepared for this event and not even a balloon was launched to study the properties of the layer during its early stages. An airplane can not fly through a fresh volcanic plume, but after the initial ash plume has dissipated, airplanes can safely pass through the gas and aerosol remnants. From a scientific point of view, it is important to measure the formation and development of the sulfate aerosol. This might involve using lidar to measure the particle characteristics in early stages. After the ash has fallen out, in-situ studies of gas and particle properties would be preformed. It is conventional wisdom that a violent volcanic eruption inserts silicates and sulfur bearing gases into the stratosphere. Photolytic reactions then generate sulfuric acid that nucleates to form small particles. These sulfuric acid particles coagulate and grow and form the relatively long-lived volcanic cloud. However, recently it has been questioned whether or not silicates are a significant component of the early stratospheric cloud. Clearly it is important for climate modelers to know the composition of the particles, particularly in the important initial phase of the cloud. These measurements can only be made in situ. Furthermore, the amount of chlorine in some volcanic clouds is so great that one would expect the ozone layer to be essentially destroyed by it. That this does not occur is a major puzzle in atmospheric chemistry. It has been postulated that the chlorine is removed in the volcanic plume by dissolving into water droplets before the plume reaches the stratosphere. It would be valuable to measure the amount of chlorine in the stratosphere shortly after a volcanic eruption.

Forest Fires

A second example is the analysis of the stratospheric particulates inserted by pyrocumulonimbus triggered by forest firesSuch material is organic in nature. The quantity and nature of this material has not been quantified. Recently there has been a great increase in interest in forest fires among the atmospheric community [Fromm et al, 2004]. In-situ data has been used to show that high latitude fires inject organic materials into the stratosphere [Jost et al, 2004]. Strangely, there seems to be little evidence of stratospheric injections of materials from tropical fires. Murphy et al. (1998) showed there is a layer of organic aerosols in the upper troposphere, below the tropopause, but these aerosols do not seem to get into the stratosphere. Why are they not observed in the stratosphere? It has been suggested that they are destroyed by the higher ozone levels.

Disasters

A third scenario illustrating the value of a standing stratospheric aerosol observatory on SOFIA is afforded by the oil fires in Kuwait after the first gulf war. To carry out a study of the aerosols being inserted into the atmosphere, an aircraft was quickly outfitted to make measurements at great expense. Once again, had a quasi-permanent facility been available, this would have led to a savings in time and money. It is unfortunately true that given the present geopolitical situation, more serious scenarios are easily imagined. It is not unreasonable to fear that a disaffected group could ignite a nuclear weapon. If such an unfortunate event were to occur, it would be extremely important to be able to respond immediately and to measure the spread of radioactive aerosol particles. Such a capability could be of interest to the Department of Energy and Homeland Security.

Troposphere/Stratosphere exchange

Understanding the dynamical, chemical and physical processes that control water vapor, ozone, radical constituents, aerosols, and clouds and their impact on the radiative balance of the Upper Troposphere and Lower Stratosphere (UTLS) is critical for advancing the reliability of predictions of climate change or of trends in global air quality. The UTLS is a highly coupled region: dynamics, chemistry, microphysics and radiation are fundamentally interconnected. Characterizing the transport processes and their contribution to the constituent distribution in the UTLS is an important first step toward a better quantification of chemical and microphysical processing in this region.

Water vapor is the most important greenhouse gas. Detailed understanding of the water cycle and water transport into the stratosphere is important for prediction of future climate change. Both radiative forcing and chemistry are affected by water vapor in the stratosphere. Stratospheric water vapor concentrations have an effect on both the production of OH radicals and the formation of polar stratospheric clouds, which modulate polar ozone destruction. In the stratosphere H_2O is also created by methane oxidation. Remote sensing and in-situ measurements indicate a trend of increasing water vapor concentrations in the stratosphere in recent decades that can not be fully accounted for by the increased methane concentration.

SOFIA will spend most of the flight time in the tropopause region, where exchange between the stratosphere and troposphere occurs and offer a unique opportunity to perform detailed studies of these exchange processes over long periods of time, potentially detecting a climate change signal. Instruments measuring trace gases such as ozone, water, carbon monoxide, nitrous oxide, reactive nitrogen, hydrocarbons, halocarbons, sulfur compounds, and organic nitrates will provide valuable insights. Augmented by the above aerosol observatory and measurements of HCl, water isotopes and radon gas, SURF offers to provide clues to still poorly understood atmospheric processes that are crucial for our understanding of climate change.

Cost

The cost of augmenting the SOFIA mission to add a SOFIA Upper Deck Research Facility capability is less than \$200 million. We estimate that initial cost to modify the aircraft to carry the proposed instruments will range from \$2 million to \$25 million, depending on the range of scientific experiments desired, the required level of modifications, and the necessary FAA certification requirements for safe installation and use. At the lower end of $2 million dollar, some window plates with gas inlet assemblies and optical windows, power outlets, and instrument racks and enclosing facilities would be installed on the upper deck, with designs copied from the existing water vapor monitor, to accommodate a range of existing instruments. For an additional $1-10 million, autonomous instruments could be designed specifically for use on SOFIA, including full FAA certification for permanently installed instruments. In a full development, at a total cost of $25 million, instruments would be designed and built to FAA specifications, and the cargo bay would be modified also to carry instrument containers and provide downward looking optical window ports as well as sample inlets. In addition, the upper deck would be modified with upward looking optical window ports for lidar and other remote sensing needs. Other instruments could also be funded as part of other science programs.

Operational cost will be much less than for regular instrumented aircraft, because the aircraft hours are covered by the astronomy research. Cost that will occur are program management and technical support of investigators for instrument installation and operation, estimated at 4 FTE ($1.2 million/year).

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Appendix

List of contributors to the "SOFIA Upper Deck Science Opportunities Workshop" at NASA Ames Research Center on June 22 - 23, 2004. More details about the workshop can be found at http://surf.arc.nasa.gov

Linnea Avallone, LASP/University of Colorado, Boulder, CO; Measurements from In-Service Aircraft: What are the Possibilities?

Douglas S. Baer, Los Gatos Research, Mountain View, CA; Novel instrumentation for trace gas measurements based on cavity enhanced absorption spectroscopy (Poster)

Albert Betz, University of Colorado, Boulder, CO; Thermospheric Oxygen Mapper (TOM)

Donald R. Blake, University of California at Irvine, Irvine, CA;Compact, autonomous whole air sampler for trace gas studies aboard the SOFIA aircraft (in absentia)

Jesse Bregman, NASA Ames Research Center, CA;The capabilities, limitations and constraints of SOFIA

T.Paul Bui, NASA Ames Research Center, CA; In situ meteorological and turbulent measurements for the SOFIA Upper Deck (in absentia)

Tim Castellano, NASA Ames Research Center, CA; Transitsearch: A Collaboration with Amateur Astronomers to Discover Transiting Extrasolar Planets

Robert Chatfield, NASA Ames Research Center, Moffett Field, CA;Science that SURF Can Advance: A Modeler's Thoughts about the Next Decades

Ronald Cohen, Department of Chemistry, Berkeley, CA; Observing Trends in Nitrogen Oxides: A unique opportunity from SOFIA (in absentia)

James W. Elkins, NOAA/CMDL, Boulder, CO, Climate Change Studies of Important Trace Gases

Kenneth Alan Frank, Astronomical Association of Northern California, CA

A. Gannet Hallar, NASA Ames Research Center, CA; Measurements of Aerosol Optical Properties using Cavity Ring Down Technology

Jason P. Hatton, Association of Lunar and Planetary Observers (ALPO), San Francisco, CA; Digital video imaging with small telescopes

Pat Hamill, San Jose State University, CA; An aerosol observatory on SURF

Robert L. Hawkes, Mount Allison University, Sackville, Canada; Meteoroid Structure: Current Views, Astrophysical Importance and SOFIA Possibilities

R. Stephen Hipskind, NASA Ames Research Center, CA; Earth Science Roadmap & Suborbital Platform Program

Chris A. Hostetler, NASA Langley Research Center, Hampton, VA (A) Lidar applications on SOFIA

Laura T. Iraci, NASA Ames Research Center, Moffett Field, CA; Chemical Composition of Upper Tropospheric and Lower Stratospheric Aerosols

Peter Jenniskens, SETI Institute, Mountain View, CA; Towards a SOFIA Upper Deck Research Facility; Meteor research enabled by airborne AIM-IT rapid pointing technology

Hansjuerg Jost, BAER Institute, Mountain View, CA; SOFIA Upper Deck Science Opportunities in the Earth Sciences

Kenneth W. Jucks, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA; FIRS-2 remote sensing from SOFIA

Armin Kleinboehl, University of Bremen, Germany; Radiometry of atmospheric chemical composition from SOFIA

Mike Koop, San Jose Astronomical Association, San Jose, CA

Mark A. Kritz, ASRC/SUNY, Los Gatos, CA; A success story - fourteen years of piggybacking aboard NASA's Kuiper Airborne Observatory

Michael J. Mahoney, JPL/Caltech, Pasadena, CA; Where Is The Tropopause?

Howard Matis, Lawrence Berkeley National Laboratory, Berkeley, CA (A) Using SOFIA to introduce teachers and students to cosmic ray science

Thomas J. McGee, NASA GSFC, Greenbelt, MD (A) Compact Lidar for Stratospheric Ozone

Thomas J. McGrath, The Boeing Company/Phantom Works, Seattle, WA

Marty Mlynczak, NASA Langley Research Center, Hampton, VA Far-Infrared Spectroscopy of the Troposphere for SOFIA

Pilar Montañés-Rodríguez, Big Bear Solar Observatory, Big Bear City, UT; Earthshine Observations from SOFIA

David Nugent, University of California, San Diego, CA; Near-real time meteor flux measurements from aircraft for satellite impact hazard mitigation and education

Laura Pan, National Center for Atmospheric Research, Boulder, CO; Issues of Stratosphere-Troposphere Exchange in the Middleworld

Steve Patterson, NASA Ames Research Center, CA

Leonhard Pfister, NASA Ames Research Center, CA; Air Masses Sampled by SOFIA in the lowermost stratosphere

Jim Podolske, NASA Ames Research Center, CA; Water vapor measurements

Colin Price, Department of Geophysics and Planetary Science, Tel Aviv University, Israel; Multi-spectral Optical Observations of Sprites from SOFIA

Stephen J. Reeves, The Boeing Company/Phantom Works, Seattle, WA

Frans Rietmeijer, The University of New Mexico Albuquerque, NM; What can be learned from long-term, frequent dust collection in the tropopause region?

Ray W. Russell, The Aerospace Corporation, El Segundo, CA Open questions in mid-IR astronomy and aeronomy that may be addressed in observations from SOFIA's Upper Deck (in absentia)

Ross J. Salawitch, Jet Propulsion Laboratory, Pasadena, CA; Measurement Needs in the UT/LS

Robert A. Stachnik, Jet Propulsion Laboratory, Pasadena, CA

Hans Stenbaek-Nielsen, University of Alaska at Fairbanks, Fairbanks, AK; Results from airborne observations at 1000 frames/s

Fred K. Stroh, Institute for Chemistry and Dynamics of the Geosphere, Juelich, Germany; Scientific Return from High Spatial Resolution Mid-IR Limb Emission Measurements of the UTLS Region

Michael J. Taylor, Center for Atmospheric and Space Sciences, Utah State University, Logan, UT; Airborne Investigations of Mesospheric Gravity Waves and their Sources

Josep M. Trigo-Rodriguez, Inst. Geophysics and Planetary Physics, UCLA, Los Angeles, CA; Detection of volatiles in cometary meteoroids using IR meteor spectroscopy (in absentia)

S. Mani Tripathi, Physics Department, University of California Davis, Davis, CA; A High Altitude Air Cherenkov Telescope

Jeremie Vaubaillon, IMCCE, France; Meteoroid impact hazard mitigation and meteor shower activity forecasting (in absentia)

Pao K. Wang, University of Wisconsin-Madison, WI; Transport of Chemical Species from the Troposphere to the Stratosphere by Deep Convective Clouds.

Chris Wiltsee, SOFIA Program Office, NASA Ames, CA